Chapter 2
Laminate Concepts & Mechanical Properties

Abstract Inspired by the successful application of ARALL and GLARE on aeronautical structures, many researchers and scientists have pursued the development of FML concepts. The fact that the majority of these studies never reached maturity on structural applications may be explained by the observation that FML was mostly treated as a material concept. As a result, not enough consideration was given to the final structural applications. Nonetheless, many FML variants with their properties presented in the literature constitute valuable information for future developments. Therefore, an overview of all the FMLs and the most characteristic properties are given in this chapter.

2.1 Introduction

The early development process of the FML concept has been described in detail by Vlot [1] and Vogelesang [2] who discuss the development of ARALL and GLARE. With these descriptions in mind, it is interesting to look at the FML concepts presented after the introduction of ARALL and GLARE. It is evident that not only the FML community described in [1] contributed to FML development.

Inspired by this successful concept, many researchers all over the world have pursued research on various FML types to investigate the behaviour of these materials under mechanical-, thermal- and environmental loading. As a consequence, the list of internationally refereed journal papers concerning FMLs has become impressive. However, there seems to be an enormous gap between the work reported in these journals and the work being done by institutes and companies on actual FML applications.

To some extent, this gap may be attributed to the apparent lack of relation between the research performed and real applications. However, it appears that some misperceptions often confused the development process of FMLs, both outside and within the FML community described in [1].

A lot of academic research reported in the literature describes a selection of experiments or (numerical) analyses on a particular combination of metallic and fibre-reinforced polymer constituents. The research topic is approached with a

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specific scientific question or objective in mind. Often this leads to detailed understanding of a particular problem. However, despite claims and conclusions, the investigated combination of materials never leads to actual applications, because of the lack of a thorough development process towards applications that addresses all relevant engineering aspects.

Applied research on the other hand, often approaches the material concept from the perspective of particular design criteria or problem. In an attempt to obtain a specific behaviour, the nature of the hybrid laminates seems to be neglected and the scope of research limited. As a consequence, the possible design options remain limited.

The misperception appears to be related to the question whether the FML is primarily a material, or whether it should be considered a structural concept. In later chapters, this is illustrated when discussing the development of theories and prediction models for various FML properties. The FML is considered either a homogeneous material, or the models treat layers individually. The denomination 'first- and second-generation FMLs' and 'next generation FMLs' [3] suggests that the state-of-the-art FMLs (ARALL and GLARE) will be replaced in time by new and advanced FMLs. As a result, the quest was to develop advanced alternatives by applying different fibre types, different metals or alloys and different adhesive types, where the advancement was expressed as increase in material properties. Therefore, the objectives of these developments often were to create FMLs with better static properties and better fatigue resistance than GLARE [4].

In the end, although people often did have potential applications in mind, most research on FML variants has been performed independent of actual applications and their requirements. As a consequence, FML types have been studied that never led to application and never reached a technology readiness level beyond 3 [5]. A more appropriate objective in the FML research would have been to gain better compliance with design criteria for aeronautical structures, and to aim for weight savings for current structural applications.

Nonetheless, the wide range of FML variants studied and reported form an impressive database of information on the potential ranges of properties that can be achieved. It would therefore be foolish not to present a review of the available data in this book.

2.2 Aluminium with Epoxy-Based Adhesive Systems

The first patented FML concept, ARALL, combined aramid fibres with aluminium sheet materials and was initially developed for a Fokker F27 wing application. This concept has been thoroughly investigated especially with respect to its fatigue characteristics [6]. Developing the concept for fuselage applications, however, revealed poor fatigue resistance due to compressive cycle-induced fibre failure. Subsequent development led to the FML based on glass fibres, named GLARE [7].

Because these two FML types, which are often denoted as the first- and second-generation FML [3], have dominated the research and development of the

FML concept in the past decades, an overview of these specific FML types will be given first.

2.2.1 ARALL and GLARE, Codes and Standardisation

In general, FMLs have been treated as a material family, consisting of thin metal layers with in-between fibres embedded in an adhesive system. From the introduction of the first concept (ARALL) onward, trade names have been filed to describe the laminates developed. However, the introduction of trade names for particular configurations seems to add to confusion.

For example, GLARE has been defined by Roebroeks in [8] as the FML based on unidirectional S2-glass fibres embedded in FM94 adhesive (manufactured by Cytec). This is in principle another material system than originally introduced by him in [7] based on the AF163-2 adhesive (manufactured by 3 m). The AF163-2 system was selected at the time based upon the observed high resistance against delamination obtained in an optimization study. Nevertheless, the FM94 adhesive system has been adopted for the FML application on the Airbus A380 for cost reasons.

Indifferent of the reasoning for selecting FM94, it should be noted here that neither the trade name GLARE, nor the grading (GLARE1, GLARE 2, etc.) changed when the other adhesive system was adopted. Technically, the question rises whether the proposed coding is sufficient to describe the material composition. In fact, the aluminium alloy, the fibre type and the adhesive system are only implicitly considered in the name and grading, but are not explicitly defined. It seems that the freedom of tailoring the FML concept similar to the tailoring of fibre-reinforced polymer composites conflicts with the approach adopted in the metal world to code each material.

To illustrate the issue, one may for instance take a closer look at GLARE. As the name indicates, GLARE is a laminate consisting of aluminium reinforced by glass fibres. In general, this could be any combination of glass fibres, aluminium alloys and adhesive systems, as it has not been defined explicitly. Within the community involved in development of GLARE for the A380 [1], the application of unidirectional S2-gass fibre/FM94 epoxy prepreg has always been considered in combination with aluminium 2024-T3, see Table 2.1.

However, a study has been published on the aging effect with fatigue of GLARE [11], where instead of unidirectional prepreg, woven fabric was applied, see Fig. 2.1. It may still be considered GLARE, but the observed behaviour might not directly relate to experimental observations for GLARE based on unidirectional prepreg. For example, the delamination behaviour at the metal/fibre interfaces for unidirectional prepreg and fabric is known to be different [6, 12].

Another example here is the introduction of so-called High Static Strength (HSS) GLARE [10], which is composed of 7475-T761 alloys with the same S2-glass fibres as in GLARE, but in a different high-temperature curing epoxy system. Although presented as an evolution in [10], it mostly comprises a variation similar to

Table 2.1 Standardized ARALL and GLARE grades [7–10]

Grade	Alloy	Metal thickness	Fibre orientation	Fibre	Epoxy	Curing (°C)	Condition
ARALL-1	7075-T6	0.3	0/0	HM aramid	AF163-2	120	0.4% post-stretched
ARALL-2	2024-T3	0.3	0/0	HM aramid	AF163-2	120	As-cured
ARALL-3	7475-T761	0.3	0/0	HM aramid	AF163-2	120	0.4% post-stretched
ARALL-4	2024-T81	0.3	0/0	HM aramid	AF191	175	As-cured
GLARE1	7075-T6	0.3–0.4	0/0	S2-glass	FM94	120	Post-stretched
GLARE2A	2024-T3	0.2–0.5	0/0	S2-glass	FM94	120	As-cured
GLARE2B	2024-T3	0.2–0.5	90/90	S2-glass	FM94	120	As-cured
GLARE3	2024-T3	0.2–0.5	0/90	S2-glass	FM94	120	As-cured
GLARE4A	2024-T3	0.2–0.5	0/90/0	S2-glass	FM94	120	As-cured
GLARE4B	2024-T3	0.2–0.5	90/0/90	S2-glass	FM94	120	As-cured
GLARE5	2024-T3	0.2–0.5	0/90/90/0	S2-glass	FM94	120	As-cured
GLARE6A	2024-T3	0.2–0.5	+45/−45	S2-glass	FM94	120	As-cured
GLARE6B	2024-T3	0.2–0.5	−45/+45	S2-glass	FM94	120	As-cured
HSS GLARE3	7475-T761	0.2–0.5	0/90	S2-glass	FM906	175	As-cured
HSS GLARE4A	7475-T761	0.2–0.5	0/90/0	S2-glass	FM906	175	As-cured
HSS GLARE4B	7475-T761	0.2–0.5	90/0/90	S2-glass	FM906	175	As-cured

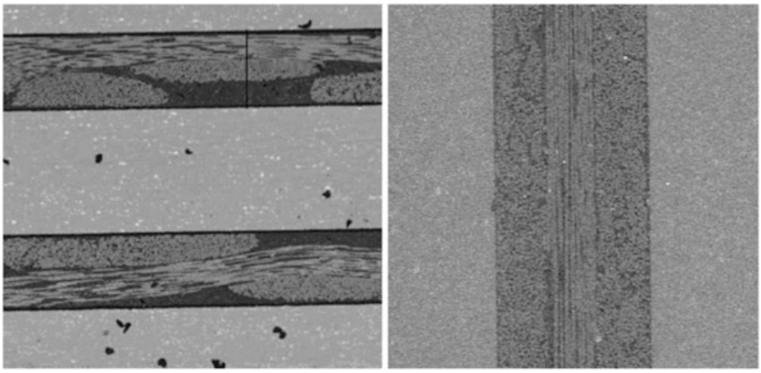

Fig. 2.1 Cross sections of GLARE laminates based on woven fabric [11] (*left*) and based on unidirectional prepreg (*right*)

the variation initially applied to ARALL, where 7475-T761 and 175 °C curing systems were already exploited for specific FML types. In fact, the origin of HSS GLARE is related to the higher static strength compared to standard GLARE, reducing the fatigue crack initiation life provided by the latter one considerably.

Because of the increased laminate variations, Airbus, for example, changed the laminate designations to 2024-FML, 7475-FML and 1441-FML, instead of the traditional names GLARE and HSS GLARE

These examples illustrate that the FML concept, or even the FML family, is not a family of materials, but a structural laminate concept. Depending on the structural applications, a specific combination of alloy, fibre and adhesive may lead to optimal performance of the structure, which does not necessarily translate to an overall increase in mechanical properties at material level. The reader should bear this in mind when reading this chapter on the laminate concepts and their properties.

2.2.2 Aramid Fibres (ARALL)

The FML ARALL, initially developed for lower win skin of the Fokker F27 and F50 [1], was the first laminate concept that achieved a structural application, which was on the C-17 cargo door. This made ARALL the first concept to successfully navigate through the process of material specification and qualification, allowable determination, and development of design and manufacturing principles [10].

Although for the qualified ARALL laminates the constituents are specified, see Table 2.1, different materials have been considered in the early development. Marissen investigated the performance of ARALL laminates containing aramid prepreg and fabric, where in the latter case the laminate was manufactured by placing the dry fabric between structural adhesive films [6]. In his research, the fibre volume fraction of the Twaron HM aramid layer was subject of investigation, while in addition different adhesive systems were applied. Although in the end AF163-2 from 3 m was selected for ARALL-1 to ARALL-3, initially BSL-312-UL from Cyba-Geigy and FM123-5 from American Cyanamid were considered.

In the context of Marissen's research where the shear deformation of the resin-rich layer at the interface between aluminium and fibre layer was deemed important for fatigue crack propagation, Mangkoesoebroto [13] observed that increasing the resin-rich layer thickness increases the delamination resistance of that interface. That, and the observed difference in delamination resistance between unidirectional fibre plies and woven fabrics [6, 12] created different fatigue crack growth characteristics between the ARALL laminates containing prepreg and the ones with woven fabric.

The typical mechanical properties of the commercial ARALL laminates are presented in Table 2.2. The values given in this table relate to the 3/2 lay-up based on 0.3 mm aluminium. A first estimation of the properties for different lay-ups or aluminium layer thicknesses can be made using a rule of mixtures and the appropriate constituent properties, i.e. aluminium and directional prepreg layers.

Table 2.2 Typical mechanical properties of ARALL laminates with 3/2-0.3 lay-up [9, 14, 15]

	Property	Orientation	ARALL-1	ARALL-2	ARALL-3	ARALL-4
Tension	σ_{ult}	L	800	717	828	731
		LT	386	317	373	338
	$\sigma_{0.2}$	L	641	359	587	373
		LT	331	228	317	317
	E_t	L	67.6	64.1	68	64.1
		LT	48.3	49	51	49
	ε_{ult}	L	1.9	2.5	2.2	2.6
		LT	7.9	12.7	8.8	4.6
	ν	L	0.33	0.32		
		LT	0.25	0.26		
Compression	$\sigma_{0.2}$	L	372	262	345	
		LT	393	234	365	
	E_c	L	70	67	66	
		LT	52	52	50	
Shear	$\tau_{0.2}$	L		117		
		LT		114		
	G	L	17	17		
		LT		16		
Blunt notch	σ_{net}	L	497[a]	401[a]		
		LT				
Bearing	$\sigma_{ult,e/D=2.0}$	L	655	531		
		LT	703	545		
	$\sigma_{ult,e/D=3.0}$	L	738	565		
		LT	724	545		
	$\sigma_{yield,e/D=2.0}$	L	586	386		
		LT	607	386		
	$\sigma_{yield,e/D=3.0}$	L	703	455		
		LT	669	441		

[a]Material not produced by ALCOA

From the values for the L and LT orientation of the laminates, the directionality of the laminates is evident. The ARALL laminates, initially developed for lower wing skin panels, have fibres oriented in one direction, providing very high strength and (tangent) stiffness in fibre direction, but significantly less in the transverse direction.

Evident in Table 2.2 and typical for FMLs is the high yield strength for unidirectional laminates. However, a remark must be made here. The yield strength here and in most literature is presented as intersect between the stress–strain curve and the 0.2% strain offset of the elastic curve.

Figure 2.2 illustrates that despite the fact that plasticity in the metal layers of the FML starts at a lower stress compared to monolithic aluminium, the lower stiffness and the higher tangent modulus result in a higher 0.2% strain offset stress for the

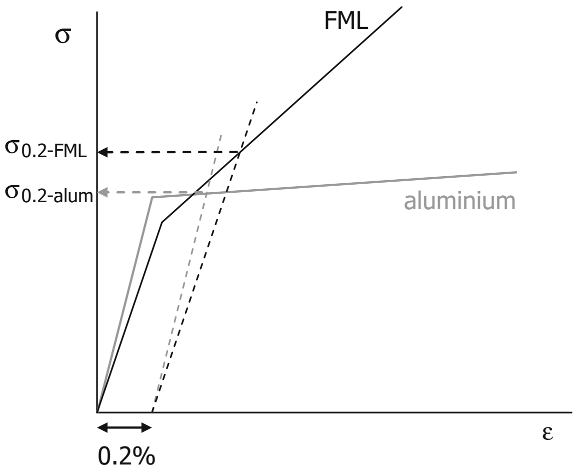

Fig. 2.2 Difference between the 0.2% strain offset yield strength for aluminium and FMLs

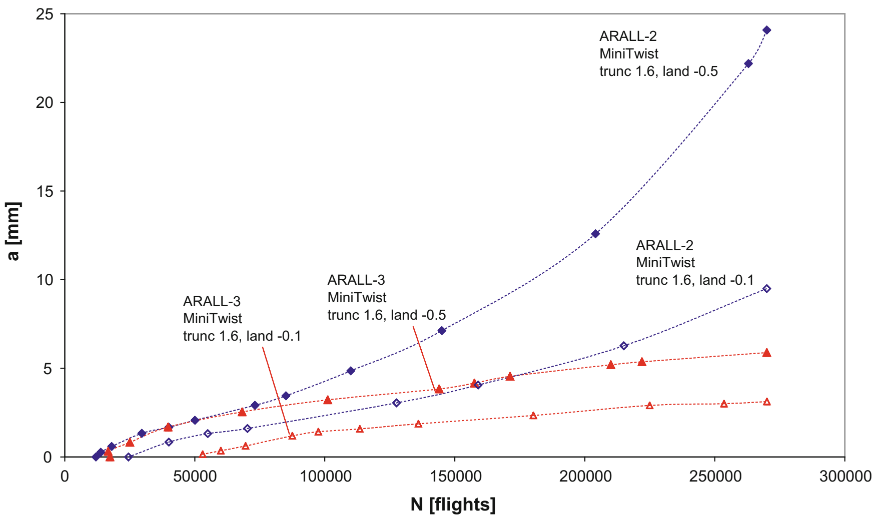

Fig. 2.3 Crack propagation curves for the ARALL-2 and ARALL-3 laminates tested at two different ground stress levels (landing); data from [16]

FML. This means that stress engineers must consider how the yield strength is implemented in their definition of allowables and what that implies for their structural sizing.

As a consequence of the initial objective of FML development, the fatigue resistance was improved with ARALL laminates in particular when post-stretching was adopted. The crack growth resistance for the post-stretched laminates is significantly higher than for monolithic aluminium. Figure 2.3 illustrates the difference in crack growth between as-cured ARALL-2 and post-stretched ARALL-3 subjected to wing load spectra.

The fatigue resistance, or more specifically, the fatigue initiation resistance, of ARALL-2 is less than that of monolithic aluminium, while it is superior for the post-stretched ARALL-3 laminates. The relatively high stiffness of the aluminium layers compared to the overall laminate stiffness creates a higher cyclic strain cycle in the aluminium layers, compared to monolithic aluminium. This means that nucleation of fatigue cracks can occur earlier in as-cured laminates.

On the other hand, the reversal of internal residual stresses induced by the stretching technique creates compressive residual stress in the aluminium layers that effectively reduces the mean stress of the fatigue stress cycle. As a consequence, the nucleation of cracks is delayed.

The durability of ARALL laminates is mainly dictated by the corrosion resistance of the applied aluminium alloys and the moisture absorption characteristics of the aramid fibres. Whereas the 7475-T761 has better exfoliation corrosion characteristics than the 7075-T6, in general the corrosion resistance of ARALL can be increased by applying cladding to the outer aluminium layers. This implies that the laminates are manufactured from bare aluminium inner layers and aluminium with single-sided cladding as outer layers.

Note that the FML properties provided in this section are for laminates tested either in the L or LT direction. The reader should bear in mind that for structural justifications the off-axis properties are of equal importance. The subject of off-axis loading is discussed in later chapters.

2.2.3 Glass Fibres (GLARE, Central)

The GLARE laminates (Table 2.3) were developed to overcome the poor fatigue performance of ARALL laminates in case compressive load cycles occur in the load spectrum. The compressive stability of the ARALL fibres in combination with the adhesion characteristics between fibre and epoxy caused fibre failure under fatigue load spectra with either low stress ratios or with compressive load cycles. The advancement of the glass fibre application in the FML concept therefore relates directly to the higher compressive stability of the glass fibres.

The application of glass fibres instead of aramid fibres in itself would not have been sufficient for filing a new patent [17], because the glass fibres were mentioned in the original ARALL patents. However, the fact that the glass fibres exhibit strain rate effects that significantly increases the impact performance of FMLs opened the door to further develop and tailor the laminated concept.

The following glass fibres have been evaluated for application in FMLs [18]:

- S2 glass (solid and hollow)
- R-glass
- E-glass

Table 2.3 Typical mechanical properties of GLARE laminates with 3/2-0.3 lay-up [14, 19–21]

	Property	Orientation	GLARE 1		GLARE 2[a]		GLARE 3		GLARE 4[a]		GLARE 5		GLARE 6	
			2/1	3/2	2/1	3/2	2/1	3/2	2/1	3/2	2/1	3/2	2/1	3/2
Tension	σ_{ult}	L	1077	1282	992	1101	640	678	831	898	683	916		
		LT	436	352	335	307	627	666	545	562	681			
	$\sigma_{0.2}$	L	525	545	343	343	298	287	304	296	297	276		
		LT	342	333	225	209	267	260	236	225	275			
	E_t	L	66	65	67	64	59.2	56.4	58.5	56	59	51		
		LT	54	50	57	48.5	59	56.2	52.4	48.7	59			
	ε_{ult}	L	4.2	4.2	4.7	4.7	4.7	4.7	4.7	4.7	4.7			
		LT	7.7	7.7	10.8	10.8	4.7	4.7	4.7	4.7	4.7			
	ν	L												
		LT												
Compression	$\sigma_{0.2}$	L	447	424	357	367	295	292	316	317	283			
		LT	427	403	255	237	305	298	278	267	280			
	E_c	L	63	67	67	65.6	61.6	58.9	59.1	57.2	61			
		LT	56	51	57	53.2	62.1	59.6	54.4	51.7	61			
Shear	$\tau_{0.2}$	L			122	112	125	115	111	100				
		LT			122	112	125	115	111	100				
	G	L			16.1	13.6	18.4	16.4	15.6	13.4				
		LT			16.1	13.6	18.4	16.4	15.6	13.4				
Blunt notch	σ_{net}	L			645	694	470	481	562	589				
		LT			278	253	454	467	396	396				

(continued)

Table 2.3 (continued)

	Property	Orientation	GLARE 1		GLARE 2[a]		GLARE 3		GLARE 4[a]		GLARE 5		GLARE 6	
			2/1	3/2	2/1	3/2	2/1	3/2	2/1	3/2	2/1	3/2	2/1	3/2
Bearing	$\sigma_{ult,e/D=2}$	L		832		703		782						
		LT												
	$\sigma_{ult,e/D=3}$	L			1019	980	1050	1018	972	931				
		LT			1013	973	1050	1018	1003	968				
	$\sigma_{yield,e/D=2}$	L		713		530		545						
		LT												
	$\sigma_{yield,e/D=3}$	L			723	729	682	680	651	643				
		LT			557	528	682	680	593	575				

[a]Laminate type A, see Table 2.1

The S-glass and R-glass have similar characteristics, while the E-glass has a lower stiffness and strength. For the FMLs for primary aeronautical structures, the stiffness is important, and often it is desired to have an FML stiffness close to the stiffness of monolithic aluminium. A small stiffness difference between aluminium and FMLs allows the application of FML skin with aluminium backup structure, without having the risk of fatigue damage in frames and stringers.

In an attempt to develop the FML concept further for thick lower wing panels, alternative lay-up concepts have been developed. Building up thick panels from thin metal sheets with composite plies may imply a burden on the manufacturing processes of such large wing panels. Primarily driven by the philosophy that thicker aluminium layers had to be applied in the concept, the CentrAl concept was developed [22].

The CentrAl concept uses GLARE as inner reinforcement in a laminate with aluminium layers of up to 1.6 mm. This concept is basically similar but reversed to an earlier lower wing panel concept, where thick aluminium plates were bonded between FML facings.

Because the application of thicker aluminium layers implied higher load transfer in case of fatigue crack growth, very large delaminations were observed, making fibre bridging ineffective. The required increase in delamination resistance of the aluminium prepreg interface was created by adding more resin to the interface in a so-called resin-rich layer. This concept is based on the earlier mentioned report by Mangkoesoebroto [13] who observed this improvement in behaviour in ARALL. The thicker the resin-rich layer at the interface, the more the shear deformation is unconstrained, reducing the shear stress peak at the delamination tip and thus the delamination growth.

2.2.4 Carbon Fibres (CARE/CARALL)

The apparent benefit of substitution of one fibre type by another in FMLs inspired people to widen the scope of fibre types. Because of the large variation in carbon fibre types available, varying from high strength to high modulus fibres, it appeared to be an excellent step to study the behaviour of FMLs reinforced with carbon fibres [23, 24] (Table 2.4).

Over the years, several studies have been performed [23–33] that all seem to have a recurring theme in the investigation; the issue of galvanic corrosion. The combination of aluminium with carbon fibres is prone to corrosion induced by the difference in potential between the two materials. Preliminary investigations indicated that the issue of galvanic corrosion could be solved if the aluminium remains isolated from the carbon fibres. To provide the isolation, concepts have been proposed in which either aluminium layers are protected with thermoplastic polyetherimide coatings or in which additional glass fibre layers are added between the aluminium and carbon fibre layers [24]. However, these approaches still require additional measures at locations where holes are drilled and fasteners are installed.

Table 2.4 Investigated carbon fibre-reinforced aluminium laminates [24]

Fibre	Adhesive	v_f (%)	t_f (mm)	T_{cure} (°C)	Lay-up	t_{lam} (mm)	σ_{ult} (MPa)	E (MPa)
HM	AF163-2	58	0.22	120	UD –2/1	0.82	800	105
HTA	AF163-2	58	0.27	120	UD –2/1	0.82	984	89.9[a]
T300	DLS1095	60	0.20	120	UD –2/1	0.80	747	85.2
					CP–3/2	1.30	585	71.3
IM600	Fibredux 924C	60	0.105 0.21 0.315	180	UD–2/1	0.705 0.81 0.915	896 1218 1395	87.6[a] 99.3[a] 108.1[a]
T800	Fibredux 924C	60	0.2	180	UD–2/1	0.80	1030	100
					CP–3/2	1.30	728	75.1
FT700	AF163-2	55	0.23	120	UD–2/1	0.83	675	170

[a]Calculated values

A driver behind the investigation of carbon fibre application in FMLs was the excellent crack growth characteristics of such laminates. The stiffness of the carbon fibres provided ply stiffness higher than aluminium, which could not be achieved with glass fibres and aramid fibres.

There was, however, a problem to be encountered; the coefficient of thermal expansion of these fibres differed significantly from the values known for aluminium, and even glass fibres. Adding the high stiffness to the problem, extremely high tensile residual stresses were obtained after curing. In other words, carbon fibres may contribute to the crack growth phase of the fatigue life (damage tolerance), and certainly reduced the initiation life (fatigue).

2.2.5 *Polymer Fibres (HP-PE, Zylon)*

Rather than studying the application of aramid-, glass- or carbon fibres, several studies focused on the performance of polymer fibres in FMLs. For example, in the early days of the ARALL development, Meyers and Roebroeks [34] investigated the application of high-performance polyethylene (HP-PE) fibres in FMLs. They determined the stiffness of the non-impregnated and impregnated fibres to address the performance of the HP-PE fibres in an FML containing aluminium layers. From the tensile tests it appeared that the consolidated fibres had half the stiffness of the non-impregnated fibres, resulting in an FML with similar stiffness to ARALL (Table 2.5).

In addition, because of the low adhesion characteristics between the HP-PE fibres and the epoxy, the fibres failed under low compression loading. This problem was to a lesser extent observed in ARALL when developing the FMLs for wing panel applications. The research was therefore not continued.

Another polymer fibre that has been studied for FML applications more recently was the Zylon fibre [35]. Zylon is a synthetic polybenzoxazole (PBO) fibre that has

Table 2.5 Overview of studied fibre properties

	Fibre properties			Prepreg properties		
Fibre	E (MPa)	σ_{ult} (MPa)	ε_{ult} (%)	ρ (kg/dm^3)	V_f (%)	Adhesive
HM aramid (Twaron)	124	2800	2.5			
Aramid	121	2800	2.0	1.45	50	AF163-2
S2-glass	88	4400	4.7	2.0	60	AF163-2 FM94 FM906 DLS1611
E-glass	66	2350	3.6			
R-glass	88	4400	4.7	1.98	60	
HM	358	2350	0.6	1.79	58	AF163-2
HTA	238	3400	1.4	1.77	58	AF163-2
T300	230	3530	1.5	1.77	60	DLS1095
T800	294	5590	1.9	1.81	60	Fibredux 924C
FT700	700	3300	0.5	2.16	55	AF163-2
IM600	295	5400	1.7	1.79	60	Fibredux 924C
T-650/35	255	4280	1.7			
HP-PE	76–110	2980	2.7		45–92	AF163-2
ZYLON AS	180	5800	3.5			
M5	290	4000	1.5			Epoxy

a strength and modulus almost double that of Kevlar® (p-Aramid fibre) with a density equivalent to aramid fibres [36].

The decision to study the application of Zylon fibres in FMLs was primarily driven by the high stiffness and strain to failure of the fibre. The higher stiffness was required to obtain FML stiffness equivalent to or higher than monolithic aluminium. The strain to failure is generally considered the limiting parameter for residual strength. The slowly propagating cracks, for which FMLs are known, come along with a slowly reducing residual strength. One advantage of GLARE over monolithic aluminium is that the strength is very high, while the reduction in strength induced by cracks or blunt notches such as holes is gradual and relatively small. This is attributed to the strain to failure of the FML in combination with the high strain hardening and strength. The energy absorption characteristics directly influence the residual strength capability. Reduction in the strain to failure by application of high modulus fibres would increase the strength, but significantly reduce the residual strength.

However, research revealed that for an FML containing Zylon the residual stresses after curing were extremely high due to large difference between the coefficients of thermal expansion of the Zylon prepreg and aluminium. This led to high tensile stresses in the aluminium, corresponding to high compressive stresses in the Zylon layers. However, the compressive modulus of elasticity of Zylon appeared to be about half the tensile modulus. As a consequence, the linear elastic tensile behaviour of the as-cured FML was dictated by the compressive modulus of Zylon rather than the tensile modulus, with an FML stiffness equivalent to GLARE.

In production, the high toughness of the fibres induced manufacturing challenges, because milling and drilling FML panels containing Zylon fibres induces significant tool wear, but requires sharp tooling to avoid fibres being pulled out of the laminate.

2.2.6 M5 Fibres

To solve the aspect of low compressive strength and even low composite modulus of elasticity related to the polymer fibres, AKZO developed a rigid rod polymer fibre called M5 [37]. The fibre has an excellent combination of strength and stiffness, providing sufficient strain to failure to benefit from this fibre type in FMLs (Fig. 2.4).

The related studies performed at TU Delft, however, showed that the tensile strength of an M5-FML is about 34% lower compared to standard GLARE, which is primarily related to the strain to failure. The stiffness on the other hand was observed to be 13% higher [38, 39, 40]. Interestingly enough, the blunt notch strength of M5-FML is similar to that of standard GLARE, while the residual strength appeared to be somewhat lower.

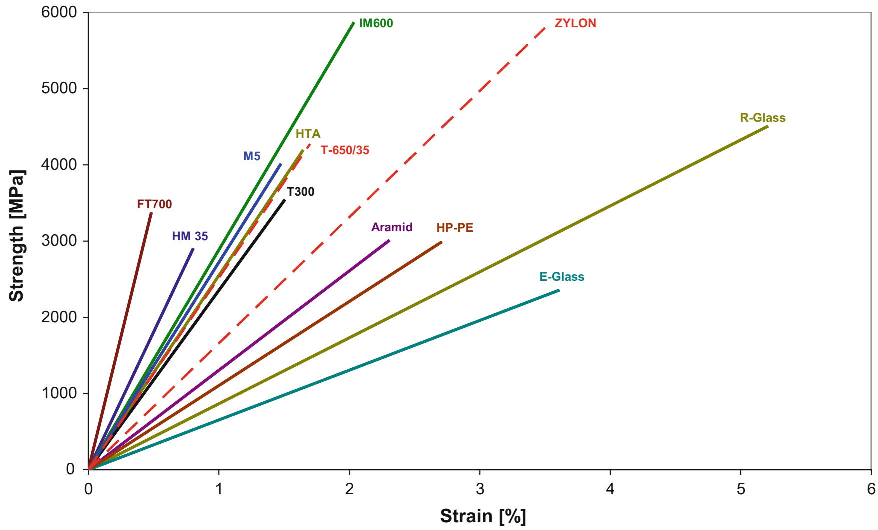

Fig. 2.4 Stress–strain curves for the fibres listed in Table 2.5, tested in previous studies

The major benefit, however, was observed in fatigue crack growth; the crack growth rates were significantly lower than those of GLARE, which were already quite low.

2.3 Other Metal Constituents

Although most work has been performed on FMLs with aluminium as the prime metal constituent, quite a number of studies report the application of other metals and alloys in FMLs. The motivation for the application of other metals may vary. Some studies are driven by seeking better stiffness compatibility with carbon fibres, or by avoiding galvanic corrosion issues when combining with carbon fibres. Other studies aim to develop FMLs for high-temperature applications, like for the high-speed civil transport aircraft or for military applications.

2.3.1 Titanium-Based FMLs

The application of titanium sheet material in FMLs has been studied a number of times. One of the first studies reporting the application of titanium is by Medenblik [27], who combined the commercial alloy Ti-6Al-4 V with a thermoset phenolic triazine resin or with a thermoplastic PEEK resin in a unidirectional FML. In evaluating the mechanical and adhesive properties, Medenblik concluded that the latter properties were greatly influenced by the surface pre-treatment of the titanium alloys. Anodization did not result in a durable oxide layer, leading to adhesive failures rather than cohesive failures.

Concerning the mechanical properties, Medenblik reported that except for the ultimate strength most properties in the longitudinal direction were comparable with the monolithic titanium properties, while in the long transverse direction they were lower. In particular, the blunt notch strength indicated high notch sensitivity, although the residual strength tests seem to show the opposite. In the end, only the fatigue performance was superior compared with the fatigue performance of the monolithic Ti-6Al-4 V.

The latter observation is in agreement with the evaluation of fatigue crack propagation and delamination growth of titanium-based FMLs as reported both by Burianek [41, 42] and by Rans [43, 44]. The fatigue performance, even at elevated temperatures, demonstrated the applicability if these laminates for high-temperature applications. Nonetheless, some of the non-reported work has also illustrated the point raised by Medenblik [27] on the surface pre-treatment of titanium.

2.3.2 Stainless Steel-Based FMLs

Stainless steel could serve as an alternative to titanium in FMLs in combination with carbon fibres. The combination eliminates galvanic corrosion as an issue, while the higher stiffness of stainless steel over titanium creates better compliance with in particular high modulus carbon fibre layers [46]. The downside of stainless steel is the higher density, which puts constraints on the maximum thicknesses of individual layers. Most studies therefore report the application of 0.1 mm AISI 316L stainless steel in FML configurations [45–47], although some studies apply thicker layers, like 0.6 AISI 304L [48].

The tensile static and fatigue properties of these stainless steel-based FMLs are generally high in comparison to aluminium-based FMLs. The high stiffness and failure strength seem to imply a significant benefit over the application of aluminium in an FML, but here one has to be careful. The thin layers, in particular the 0.1 mm thin AISI 316L layers, impose problems in compression, because the stability of these thin layers is insufficient to avoid local sheet buckling in the laminate.

Hence either thicker layers must be adopted, like in [48], which comes at the cost of significant weight, or applications must be considered which are primarily loaded in tension.

2.3.3 Magnesium-Based FMLs

Few studies report the application of magnesium in FMLs. The obvious benefit of magnesium over any of the other metal constituents is its lower density [49]. However, one should be aware that the specific properties may not substantially differ from those of many aluminium alloys. Evaluating the static and fatigue properties of FMLs based on magnesium alloys has illustrated that both the mechanical properties and the fatigue properties are similar to standard GLARE, when presented in the form of specific properties, i.e. normalizing by the densities [50].

Opposite to the application of thin stainless steel sheets in FMLs, where applications primarily loaded in tension should be considered, it seems that magnesium-based FMLs may excel mostly in compression dominated structures. The lower density of the magnesium allows to apply layers which are thicker than traditionally considered for aluminium-based FMLs, which can improve the compression stability of laminates substantially. In particular if a hybrid concept is adopted where the internal metal layers are made of magnesium, with only the outer layers made of aluminium [51].

2.4 Thermoplastic Adhesive Systems

Most of the FML research concerns the utilization of thermoset matrix systems for the composite plies. The application of thermoset-based composites is widely accepted in the aeronautical industry and only recently have structural concepts been developed based on thermoplastic systems.

However, some studies evaluate the application of thermoplastic matrix systems in FMLs. The primary problem to cope with is the required high curing temperatures to consolidate the composite. For most high-strength aluminium alloys, these high curing temperatures imply heat treatments to the aluminium with detrimental consequences for its mechanical properties. For example, a preliminary study by Van Velze [52], who investigating the mechanical properties of ARALL laminates with PEI, PPS and acetal copolymer as matrix system, revealed that the higher curing stresses negatively impact the mechanical and fatigue properties. In post-stretched condition, the thermoplastic ARALL laminates performed similar to post-stretched ARALL based on AF163-2 epoxy matrix. The only benefits that could be demonstrated at the time were absence of fibre failure in fatigue testing as-cured laminates, and the improved fatigue performance at elevated temperatures up to 190 °C.

Because high curing temperatures limit the application of various aluminium alloys, most studies seem to focus on the application of carbon fibre embedded in thermoplastic matrix system combined with titanium in an FML. Titanium alloys can be operated at higher temperatures and allow curing of the thermoplastic composite within the FML at higher temperatures.

Although some initial manufacturing trials and analyses were performed to determine the mechanical performance of FMLs based on titanium and carbon fibres embedded in thermoplastic matrix, [53], most research has focussed on impact performance [54, 55].

2.5 Innovative Hybridization Concepts

The concept of FMLs, combining the world of two distinctly different material classes, was innovative and advanced at the time of introduction. Nowadays, the concept is state-of-the-art and fully mature with the application on the Airbus A380.

The literature illustrates that along with the development of this hybrid concept, research is performed to increase the fundamental understanding of all mechanical and physical aspects involved with the material technology. Often prediction models, initially highly empirical of nature, are improved in parallel with the development of structural applications.

The advantage of that process is that the research receives focus from the structural application, requiring answers to more specific questions regarding the predictive capabilities of the prediction models. In the end, stress engineers need these models to substantiate the development of design principles and stress allowables. However, the drawback is that the academic research changes its horizon from medium- and long term towards the short term. To avoid tunnel vision in research, effort should be put in continuous questioning of the research performed and models developed, for its applicability and validity towards the long-term future.

To that aim, Rensma [45] investigated a selection of highly hybridized material concepts that by no means were chosen for their potential in aeronautical applications, but mainly to identify the blind spots in the understanding and modelling of FMLs at that time. The concepts investigated were selected as theoretical extrapolations on current research trends.

The review in this chapter illustrates that FML concepts were studied in which constituents were varied, but often the thickness of individual constituents was kept the same. Alternatively, studies were performed in which the constituents were kept the same, but thicknesses varied. For example, the CentrAl concept was composed of standard GLARE constituents, but the distribution of ply thicknesses throughout the laminate was changed.

For that reason, Rensma selected hybrid laminate concepts in which both constituents and thicknesses were varied in order to identify the limitations in understanding. An overview of investigated concepts is illustrated in Fig. 2.5. Combinations with aluminium, stainless steel, S2-glass fibre layers and carbon fibre

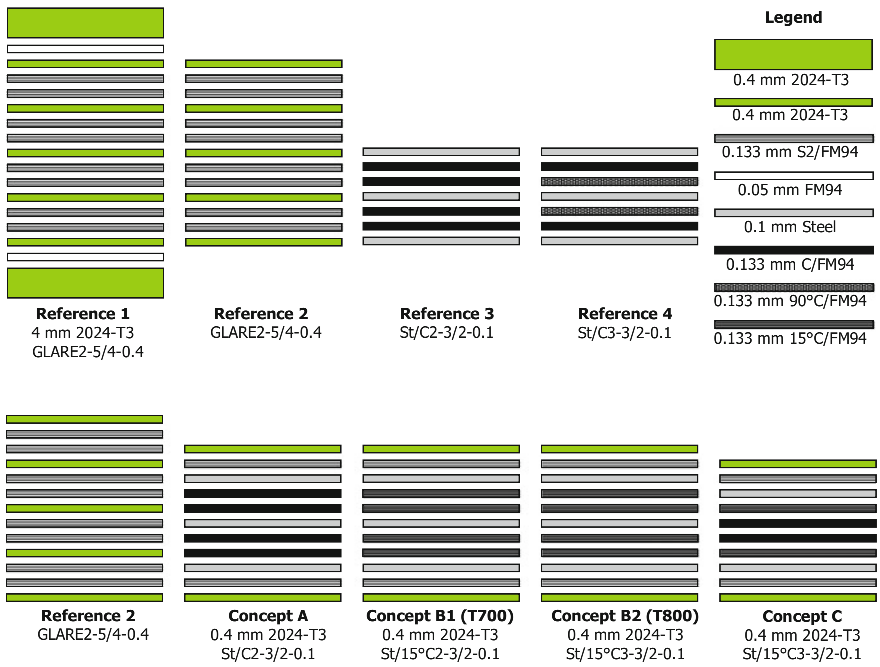

Fig. 2.5 Lay-up of hybrid concepts and the reference laminates (prepreg and adhesive thicknesses are nominal thicknesses after curing), '15°' indicates ±15° orientations

layers were considered. The overall conclusions were that trends could be predicted fairly well, but that the improvements of mechanical and damage tolerance properties highly depended on the constituents used. Some of the specific findings of this research are presented in later chapters.

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